Forward delay in scaled $Al_{0.48}In_{0.52}As/In_{0.53}Ga_{0.47}As$ heterojunction bipolar transistors

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We present experimental measurements and numerical simulations of the intrinsic forward delay as a function of base thickness in abrupt junction *n-p-n* $Al_{0.48}In_{0.52}As/In_{0.53}Ga_{0.47}As$ heterojunction bipolar transistors. For base thicknesses up to 1350 Å and impurity concentration $p=1.5\times10^{19}$ cm^{-3} we find that nonequilibrium electron transport ensures that base transit delay is less than that in the 3000-Å-thick collector space-charge region. This provides an opportunity to increase base thickness and reduce base resistance without sacrificing the intrinsic forward delay time.

Figure 1 shows a schematic band diagram of an $Al_{0.48}In_{0.52}As/In_{0.53}Ga_{0.47}As$ *n-p-n* heterojunction bipolar transistor (HBT) under forward bias. The Γ-valley conduction-band minimum CB_{min}, the subsidiary conduction-band L minimum, and the valence-band maximum VB_{max}, are indicated. This structure is of particular interest because the large conduction band offset $\Delta E_C=0.47$ eV between the $Al_{0.48}In_{0.52}As$ emitter and the $In_{0.53}Ga_{0.47}As$ base results in extreme nonequilibrium electron transport in the base. It has previously been reported that this fact results in nonclassical scaling behavior in the static (dc) characteristics of the device. For example, breakdown voltage in the collector depends on base thickness x_B (Ref. 1) and current gain scales as $1/x_B$ for devices with a thin base.[2] The physics governing these phenomena are intimately related to the temporal and spatial evolution of the nonequilibrium electron distribution initially injected into the base. In this letter, we report the effect such nonequilibrium electron dynamics has on the forward delay time of a transistor as a function of base thickness x_B.

The device structures are grown by solid-source molecular beam epitaxy on semi-insulating InP substrates using techniques described in Ref. 3. The $In_{0.53}Ga_{0.47}As$ base of thickness x_B is Be doped to $p=1.5\times10^{19}$ cm^{-3}. The $In_{0.53}Ga_{0.47}As$ collector space-charge region is $x_C=3000$ Å thick and doped to $n=1\times10^{16}$ cm^{-3}. Fabricated HBTs have an emitter stripe width of 2.5 μm.

Figure 2(a) shows measured total forward delay time $\tau_F=\tau_B+\tau_C$ as a function of base thickness 200 Å$\leqslant x_B\leqslant$4000 Å.[4] Here, τ_B and τ_C are base and collector transit delays, respectively. The delay time is obtained by fitting the measured s parameters to the equivalent circuit model shown in the inset of Fig. 2(a). The error bars are a measure of fit sensitivity to a given set of equivalent circuit parameters. We note that, although the absolute value of τ_F may slightly depend on the equivalent circuit model or the extraction method, in this letter we are only concerned with the relative change (i.e., the scaling behavior) of τ_F for different x_B.

For base thickness less than approximately 1000 Å, the total forward delay is dominated by τ_C and is therefore insensitive to variations in x_B. The measured delay time of $\tau_F\simeq\tau_C=0.5\pm0.2$ ps corresponds to an average electron velocity in the collector of approximately $v_C\simeq x_C/2\tau_C=3\times10^7$ cm s^{-1}. When $x_B\gtrsim1000$ Å the base transit delay becomes important and τ_F increases. For $x_B=4000$ Å we obtain $\tau_F=6.7$ ps and, since τ_C remains essentially constant, we estimate $\tau_B=6.2$ ps corresponding to an average forward electron velocity in the base of $v_B\simeq x_B/\tau_B=6.4\times10^6$ cm s^{-1}. Obviously, the dramatic increase in base transit time delay can only be explained by a large change in average electron velocity with increasing base thickness x_B.

To understand the physics underlying these experimental results we performed numerical simulations similar to those described in Refs. 5–7. The electrons contributing to the emitter current, I_E, are initially thermally distributed in the conduction band of the wide band-gap $Al_{0.48}In_{0.52}As$ emitter. Under forward base-emitter bias, electrons are injected with approximate excess kinetic energy $\Delta E_C=0.47$ eV into the Γ-valley conduction band of the *p*-type $In_{0.53}Ga_{0.47}As$ base. There is also the possibility that some electrons enter the base, or subsequently scatter into the subsidiary L valley 0.55 eV above CB_{min} (see Fig. 1). The probability that electrons scatter elastically from statically screened ionized *p*-type impurities or inelastically off excitations of the degenerate *p*-type majority carriers while traversing the base may be calculated using the appropriate dielectric response function.[8,9] Electrons in the conduction band may also scatter off other conduction-

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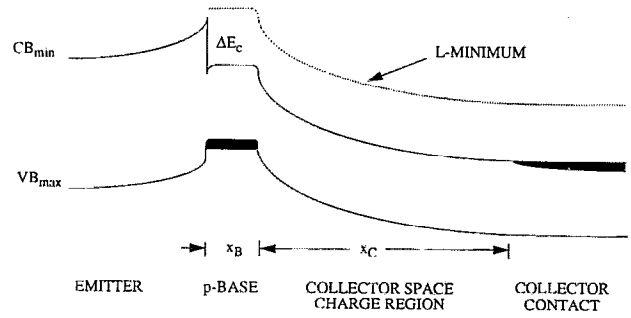

FIG. 1. Schematic band diagram of an n-p-n $Al_{0.48}In_{0.52}As/In_{0.53}Ga_{0.47}As$ HBT under forward bias. ΔE_C=0.47 eV, $p=1.5\times10^{19}$ cm^{-3}, and x_C =3000 Å.

band electrons. The model also takes into account the finite current gain of the transistor which arises from the fact that conduction-band electrons traversing the base can recombine with p-type majority carriers giving rise to base current $I_B=(1-\alpha I_E)$. Having traversed the base, electrons are accelerated in the electric field of the reverse-biased collector space-charge region. Here they may suffer inelastic collisions with phonons and other electrons. Those electrons which gain enough kinetic energy may also transfer from the nonparabolic Γ valley to the high effective electron mass L- and X-valley conduction-band minima. In our model, trajectories of electrons are determined using a semiclassical Monte Carlo algorithm in which Poisson's equation is satisfied throughout the simulation.

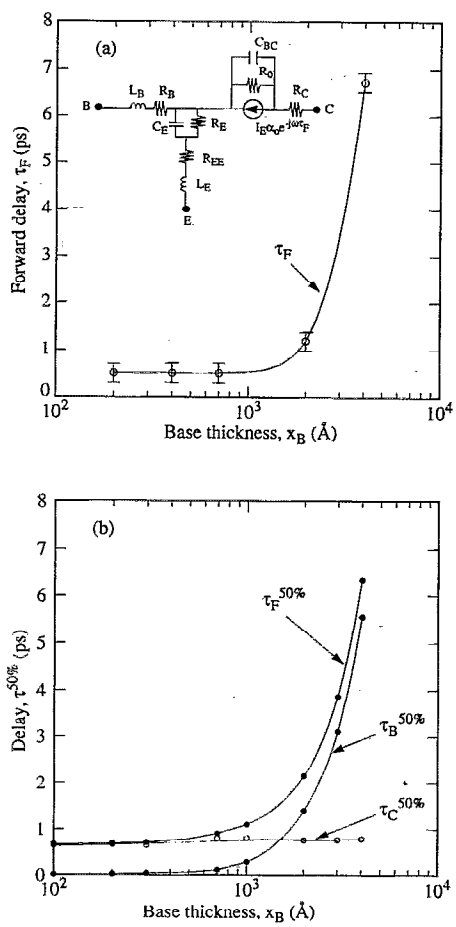

FIG. 2. (a) Small signal forward delay τ_F for different base thicknesses x_B. The measurements were carried out at emitter current density of 5×10^4 A cm^{-2} and collector-emitter voltage bias V_{CE}=1.5 V. The error bars are ±0.2 ps. The inset shows the equivalent circuit model used to model the device. (b) Results of calculating $\tau_F^{50\%}$, $\tau_B^{50\%}$, and $\tau_C^{50\%}$ as a function of base thickness for the device parameters used in the experiments.

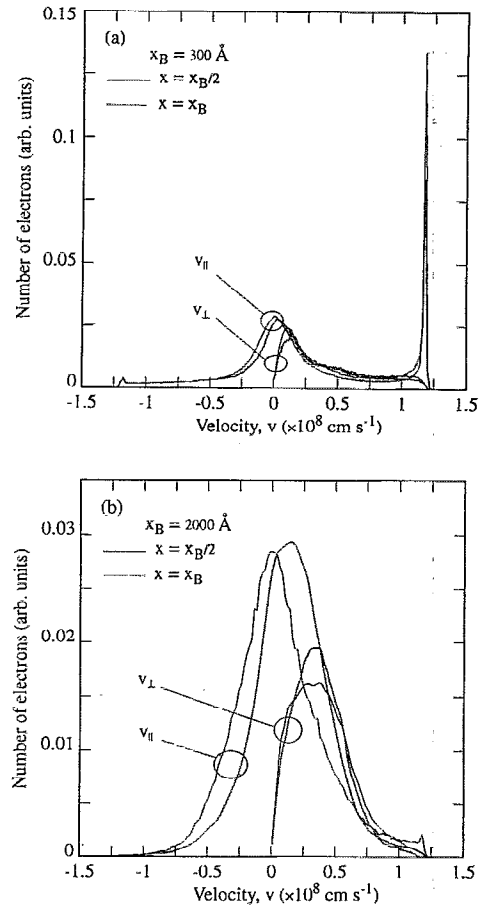

FIG. 3. Results of calculating the longitudinal (perpendicular to the plane of the heterojunction) electron velocity $v_\parallel$ and transverse electron velocity $v_\perp$ distribution in the base of an $Al_{0.48}In_{0.52}As/In_{0.53}Ga_{0.47}As$ HBT for $x=x_B/2$ and $x=x_B$ with (a) x_B=300 Å and (b) x_B=2000 Å.

In Fig. 2(b) we plot results of calculating the forward delay for 50% of step-injected current αI_E to flow through the device $\tau_F^{50\%}$. Also shown are the contributions of $\tau_B^{50\%}$ and $\tau_C^{50\%}$ as a functions of base thickness x_B. $\tau_B^{50\%}$ is the time for 50% of current αI_E to flow across the base and $\tau_C^{50\%}$ is the 50% large-signal delay across the collector. The results of our model are in good qualitative agreement with the experimental data shown in Fig. 2(a) even though the measured small-signal delay τ_F is not identical to the calculated large-signal $\tau_F^{50\%}$. The numerical simulations clearly show that, although base transit delay increases with increasing x_B, τ_B does not become greater than τ_C until $x_B\geqslant1350$ Å. In contrast, for a similar transistor but with diffusive base transport and diffusion constant D=25 cm^2 V^{-1} s^{-1}, τ_B becomes greater than τ_C when $x_B\geqslant600$ Å. Hence, the abrupt emitter/base junction HBT can have more than double the base thickness of the corresponding

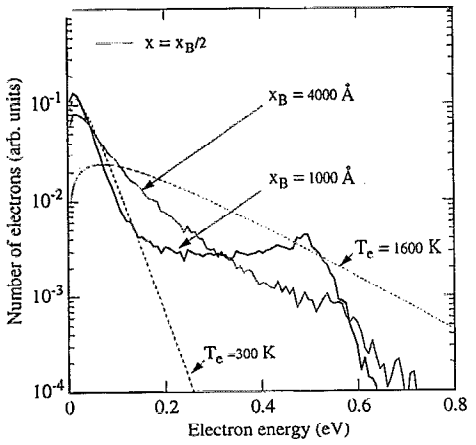

FIG. 4. Calculated electron energy distribution function at $x_B/2$ for $x_B = 1000$ Å and $x_B = 4000$ Å. Dotted curves are the thermal electron distribution corresponding to an effective electron temperature T_e.

graded junction HBT without suffering a penalty in τ_F.

To establish the role played by nonequilibrium electron transport in determining the trends in Figs. 2(a) and 2(b), in Fig. 3 we plot longitudinal and transverse electron velocity distribution in the base at $x = x_B/2$ and $x = x_B$ for (a) $x_B = 300$ Å and (b) $x_B = 2000$ Å. On the one hand, for a base thickness of $x_B = 300$ Å the peak in longitudinal electron velocity at approximately 1.2×10^8 cm s^{-1} is due to extreme nonequilibrium electron transport across the base. On the other hand, the absence of any significant high velocity peak for $x_B = 2000$ Å is a clear indication that electrons have suffered many elastic and inelastic collisions. Nevertheless, even for $x_B = 4000$ Å the electron distribution function has not thermalized to the lattice temperature $T = 300$ K. Of course, if the electron distribution could be described by some effective electron temperature T_e, we might consider introducing an effective diffusion constant $D(T_e)$ to describe electron motion. However, as illustrated in Fig. 4, such an approach fails because, even for $x_B \simeq 4000$ Å, the nonequilibrium electron distribution function *cannot* be described by an effective electron temperature T_e.

Although high-energy injection in abrupt junction $Al_{0.48}In_{0.52}As/In_{0.53}Ga_{0.47}As$ HBTs results in nonequilibrium electron transport which does, in fact, reduce base transit delay, it may not be the optimum design in a transistor if device speed is limited by resistive and capacitive parasitics. In such a case it is necessary to carefully evaluate the relative advantages and disadvantages of abrupt versus graded emitter heterostructures.[10] In a graded device the turn-on voltage is reduced by approximately ΔE_C resulting in reduced power dissipation. Furthermore, the collector current ideality factor n will be close to unity (compared to around $n = 1.5$ for an abrupt junction $Al_{0.48}In_{0.52}As/In_{0.53}Ga_{0.47}As$ HBT) resulting in a 33% reduction in emitter dynamic resistance $r_E = nk_BT/qI_E$, where k_BT is the thermal energy, and q is the electron charge. Therefore, if the base delay for diffusive transport can be tolerated, as usually occurs in a device dominated by parasitics, it may be beneficial to grade the emitter/base junction. On the other hand, it is important to note that the use of an abrupt emitter/base junction in the transistor of Fig. 1 allows for more than a factor of 2 thicker base for a given transit delay and this, of course, results in a lower base resistance. Reduction of base resistance is particularly important in devices with relatively large emitter dimensions. Thus, nonequilibrium electron transport provides an opportunity to reduce base resistance without suffering a penalty in base transit time.

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